FINAL REPORT
Turbulence Processes in the Stable Marine Atmospheric Boundary Layer

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LONG-TERM GOALS

The long-term goals of this study are to improve our understanding of turbulence processes within the stable marine atmospheric boundary layer in spatially heterogeneous coastal environments with the aim of improving numerical representation of such environments.

OBJECTIVES

The study has two distinct objectives. The first is the study of the evolving turbulence structure of the stable boundary layer as the mesoscale flow rounds a coastal headland and forms an expansion fan in which the flow accelerates and the boundary layer collapses. The region around the headland is one of extreme spatial heterogeneity – there are large changes in wind speed an order of magnitude increase in the surface wind stress, and boundary layer depth decreases by a factor of about 5. A large surface wind-stress curl drives enhanced upwelling of cold water creating a cold pool just downwind of major headlands; this increases the local stability further modifying the overlying boundary layer structure.

The second objective is to characterize the entrainment zone structure at the top of the boundary layer. Previous studies of entrainment zone structure have focused almost entirely on convective conditions; this is the first extensive study of entrainment zone structure for the stable marine boundary layer.

APPROACH

An extensive set of aircraft measurements from the Coastal Waves 96 (CW96) field campaign are being utilized for this study. Turbulence measurements from straight and level flight legs within the surface layer (30 m) define the surface forcing; measurements from extensive series of *sawtooth* profiles extending from approximately 15 m to above the inversion are used to derive both the mean and turbulent vertical structure following the approach of Tjernström (1993). The observations are interpreted in the light of numerical simulations conducted by Michael Tjernström and Stefan Söderberg at Stockholm University, Sweden.

The study of entrainment zone structure utilizes data from the NCAR SABL lidar system flown during CW96; this provides exceptionally high resolution data with which to determine the small-scale structure of the entrainment zone – 3.75 m in the vertical by approximately 5 m in the horizontal. Detection of cloud and boundary layer top is performed using a wavelet-based algorithm (Davis et al. 2000). The statistical properties of the entrainment zone will be compared with those for convective conditions available in the literature. All analysis is being conducted by Ian Brooks.

WORK COMPLETED

To date, 3 peer reviewed papers and 6 conference presentations have resulted from this project, a further 1 or 2 papers are expected to be completed over the next year.

The aircraft mean and turbulence data has been processed and both the surface layer and vertical structure compared with mesoscale model simulations conducted by Stefan Söderberg and Michael Tjernström at Stockholm University. The results of this study have been presented in two papers at the 4th AMS Conference on Coastal Atmospheric and Oceanic Prediction and Processes in Florida, November 2001 (Brooks et al. 2001; Söderberg et al. 2001) and at the 15th AMS Symposium on Boundary Layers and Turbulence in Wageningen, The Netherlands, July 2002 (Söderberg et al. 2002a,b). A paper has recently been published in Boundary-Layer Meteorology (Brooks et al. 2003)

In addition to the central study of turbulence structure, the effect of the spatial variability of surface layer turbulence forcing on the so-called surface evaporation radar duct has been assessed – the duct depth was estimated from a bulk parameterization and the spatial distribution compared with that of the directly measured turbulence forcing. The results have been published in Geophysical Research Letters (Brooks 2001).

The processing and analysis of lidar data has been completed. A new automated algorithm based on an existing wavelet covariance transform (Davis et al. 2000) has been developed that allows both the upper and lower limits of the inversion to be identified in a robust manner, while remaining insensitive to the details of vertical gradients and small-scale structure in the lidar backscatter above and within the boundary layer. A paper describing this approach has been published in the Journal of Atmospheric and Oceanic Technology (Brooks 2003). Two papers were presented at the 15th AMS Symposium on Boundary Layers and Turbulence (Brooks 2002a,b). Papers describing the results for the cloud-capped, and cloud-free boundary layer are currently in preparation.

RESULTS

The aircraft turbulence measurements were analyzed within the framework of local similarity (Nieuwstadt, 1984). It was found that a form of local similarity applied to the velocity variances in spite of the high degree of spatial variability, even through the transition from relatively undisturbed flow into an expansion fan downwind of Cape Mendocino. The scaling functions obtained were very similar in form to those obtained in a number of previous studies (Shao and Hacker 1980; Pahlow et al. 2001; Al-jiboori et al. 2002); however, the precise function differs between the studies – significantly so at high stabilities (Fig. 1a). The mesoscale model reproduced the scaling results very closely (Fig.1b). Differences between the various studies prompted a closer examination of the observations, it was found that the scaling function remained almost unchanged throughout the majority of the boundary layer, but differed substantially close to the surface (Fig. 1c). We hypothesize that this result, the differences between various studies, and the fact that all these functions depart from Nieuwstadt's theoretical result that the scaled velocities should approach constants at high stability, result from a controlled breakdown of true local scaling under the influence of non-local transport terms in the variance budget.

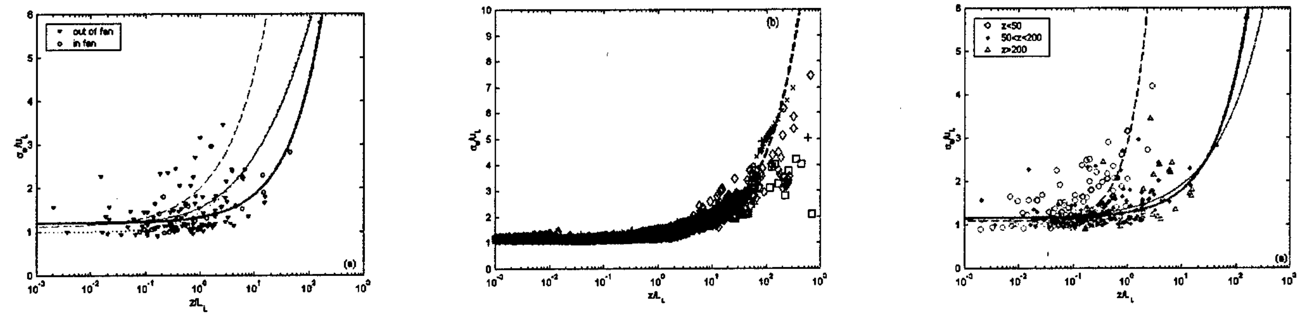

Figure 1. (a) Scaled vertical velocity variances; the heavy solid line is the best fit to all the data, other lines show the results obtained by Shao and Hacker (1980, dotted line), Al-Jiboori et al. (2002, thin solid line), and Pahlow et al. (2001, dashed line). (b) Scaled vertical velocity variances from the MISU model, the heavy dashed line is the best fit from the observations. (c) Scaled vertical velocity variances partitioned by altitude.

Differences between the observed, modeled, and simple bulk parameterizations of the surface flux fields also indicate that non-local transport terms are significant in this environment.

The study of lidar measurements of the entrainment zone has led to the development of a new algorithm utilizing a Haar wavelet covariance transform. Previous applications of this transform relied upon identifying the maximum in the transform as a function of altitude to detect the mean level of a step-like change in backscatter (i.e. the inversion). This is of limited use where the inversion depth is significant, and suffers significant bias if there are vertical gradients in the backscatter within or above the boundary layer. By utilizing information from multiple wavelet dilations we have been able to identify the upper and lower limits of the inversion while remaining insensitive to small-scale variability and large-scale vertical gradients in the background signal. This is a significant advance, and will allow much more detail to be obtained regarding inversion structure and variability than has previously been possible.

Analysis of the entrainment zone structure for both cloud-topped and cloud free cases for stable marine boundary layers has shown that the entrainment zone is much narrower than for the convective case in an otherwise similar environment. Unlike the convective case, there is no correlation between entrainment zone depth and boundary layer depth; in the cloud-capped case, however, there is an inverse correlation with the thickness of the cloud layer. This is ascribed to the vertical profile of shortwave radiative heating near cloud top, and the change in depth of the point of maximum heating with the liquid water content at cloud top, which is a function of cloud thickness. An inverse correlation also exists with a gradient Richardson number. Power spectra of cloud top heights indicate the presence of an inertial subrange — this suggests a close link between variations in cloud topan in-cloud turbulence. No such inertial subrange is observed for the variations in either inversion top or base for the cloud-free case. This indicates a fundamental difference in the driving processes for entrainment between cloudy and cloud-free cases. In the former, radiative forcing drives local buoyant convection near cloud top, although the boundary layer as a whole is stable; in the latter entrainment can occur only through shear-driven turbulence at the inversion, this is expected to be through the action of discrete Kelvin-Helmholtz wave-breaking events.

IMPACT/APPLICATIONS

The finding that local similarity scaling can be applied to spatially highly heterogeneous conditions may be applied to numerical modeling studies where local similarity can be used to provide a closure for turbulence parameterization schemes.

The finding of significant variability in surface evaporation duct depth emphasizes the need to assess such variability when determining radar propagation within the coastal zone. This is an important consideration for operational applications.

The new automated algorithm for obtaining the upper and lower limits of the inversion layer can be widely applied to other lidar data sets (and indeed to any data series where the detection of a transition zone of finite width is required), and should enable more detailed information about the small-scale structure and variability of the inversion and entrainment zone to be obtained.

TRANSITIONS

The most widely applicable product of this work is the new wavelet covariance algorithm for finding the inversion limits. This is already being adopted or considered by a number of other researchers: Rich Ferrare at NASA Langley Research Center is currently implementing the algorithm for the analysis of the LaRC lidar group's own data: Ken Davis (Penn State) and Chris Kiemle (DLR, Germany) are interested in applying it to their own lidar measurements; Petra Seibert (BOKU, Austria) has expressed an interest in applying it to high resolution radiosonde data to identify the transitions between significant layers; and Simon Vosper (UK Met. Office) is working directly with Ian Brooks to adapt the approach for determining the inversion structure from radiosonde data.

RELATED PROJECTS

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